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Laboratory Corrosion Tests Of Galvanized Steel In Concrete

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Concrete test specimens containing galvanized and black reinforcing steel were partially immersed in saturated salt solution. The results were (1) corrosion began at about the same time for both the galvanized and black (mild) steel exposed in the same concrete system; (2) the greater the thickness of zinc, the earlier concrete cracking occurs; (3) in concrete of high quality, galvanized steel caused cracking earlier than black steel.

Observations indicate that the galvanizing is either inefficient or ineffective as a galvanic anode to prevent rusting of the underlying steel in concrete.

The most significant variable in postponing concrete cracking caused by corrosion of black or galvanized steel was to increase the cement factor. There does not appear to be a half cell potential value per se, that would disclose the corrosion activity of galvanized steel in concrete.

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LABORATORY CORROSION TESTS OF GALVANIZED
STEEL IN CONCRETE

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LABORATORY CORROSION TESTS OF GALVANIZED STEEL IN CONCRETE

INTRODUCTION

Several sources report various aspects concerning the use of galvanized steel(1,2,3,4) as a means for postponing concrete distress due to corrosion of the black reinforcing steel(5,6,7,8,9). However, the various reports(1,2,3,4,9) were not consistent in indicating a significant benefit in the use of galvanized versus plain reinforcing steel in concrete subjected to salt (chloride-ion) contamination.

Zinc is a widely accepted rust protective coating in a normal atmospheric environment. Because of this demonstrated property, galvanized reinforcing steel bars have been used in concrete to reduce the rate of steel corrosion in the presence of salt.

The environment under which a galvanized reinforcing steel bar exists in concrete with a pH of about 12.5 and subject to attack by chloride-ions is one about which comparatively little is known. The corrosion of zinc is inhibited through the formation of a mixture of zinc compounds such as the oxide, hydroxide, and carbonate. In addition, the zinc can serve sacrificially to protect steel exposed through scratches and cracks. How these protective measures react in portland cement concrete in an aggressive environment is the purpose of this research.

TEST PROCEDURE

The test procedure(8) was to partially immerse the reinforced concrete specimens to a 8.9 cm (3-1/2 inch) depth in a saturated solution of sodium chloride and in plain tap water. The saturated salt solution and level of water was maintained by periodically adding water and by having an excess of salt in the bottom of the tanks. Each addition of water was thoroughly stirred into the solution. The level of the water was maintained by adding water periodically to compensate for that lost by evaporation. All tests were performed in the laboratory which has an air temperature of about 22°C (72°F). The relative humidity is assumed to range between 30% and 45%.

The specimens consisted of No. 4, or 1.3 cm (1/2-inch) diameter reinforcing steel bars imbedded in concrete bars 11.4 cm (4-1/2-inch) wide by 6.4 cm (2-1/2-inch) thick and 38.1 cm (15 inches) long. The minimum amount of cover was designed to be not less than 2.5 cm (1-inch).

The cement used was ASTM Type II, modified low alkali complying with California State Standard Specifications.

Eighty replicate specimens were cast from 10 batches of 279 kg/m³ (5 sack) and 418 kg/m³ (7-1/2 sack) concrete for the laboratory tests. One-half of each batch was steam plus water cured and the other half was water cured only. Twenty replicate samples of either black or galvanized steel were used in each test parameter of cement factor and curing.

In addition, 10 specimens were cast from 335 kg/m³ (6 sack) concrete. All had galvanized steel reinforcement. One half of the specimens were moist cured; the remainder were steam cured.

Those specimens that were steam plus water cured were subjected to a temperature of $59 \pm 3^\circ\text{C}$ ($138 \pm 5^\circ\text{F}$) for approximately 16 hours and then submerged in tap water at $25 \pm 2^\circ\text{C}$ ($73 \pm 3^\circ\text{F}$) for a total cure period of 28 days. The water cured specimens were submerged in tap water for 28 days prior to testing. The concrete mix data are shown in Tables 1 and 1a.

In conjunction with corrosion testing, concrete absorption tests were performed in accordance with Test Method No. Calif. 538-A. Some details of the absorption test have been previously reported(8). Essentially, the test consists of oven drying the concrete specimens at 110°C (230°F) and then submerging them in water during the test period. Table 2 shows the results of the concrete absorption tests.

After the specimens were placed in the testing solutions, electrical half cell potential measurements were made thrice weekly(8). The purpose of these measurements was to determine when a corrosive quantity of salt had penetrated to the metal surface, and to determine, if possible, an active (corroding) or passive (non-corroding) potential for the galvanizing existed.

For the galvanized steel specimens, the reinforcing steel was first sand blasted, weighed and then galvanized. The weight of the zinc coating was calculated from the difference of the "before" and "after galvanizing weights". The hot dip galvanizing of the steel complied with the California Standard Specifications dated January 1969, and ASTM Designation: A-123.

It was intended that the thickness of the galvanized coating be the equivalent of 610 gm/m^2 (2 ounces per square foot) which would provide an average thickness of about 0.086 mm (0.0034 inch) of zinc. However, weight measurements showed that the average amount of zinc deposited was equivalent to about 915 gm/m^2 (3 ounces per square foot) and varied from 739 gm/m^2 to 1420 gm/m^2 (2.60 to 4.65 oz/sq ft).

SUMMARY AND CONCLUSIONS

Galvanized and Black Steel

When the steel reinforced concrete specimens used in the tests were partially immersed in saturated sodium chloride solution, chloride-ion penetrated the concrete and caused both the galvanized steel and the black steel to begin to corrode at essentially the same time. In a relatively porous concrete, corrosion-caused concrete cracking required a longer time when the steel was galvanized than when it was not. In a high quality structural grade concrete, corrosion of the galvanizing hastened the time to cracking. It appears that the porosity of the concrete can govern the time to cracking; the greater the porosity the greater amount of zinc corrosion products that can be absorbed before bursting pressures can be developed.

The test results showed that irrespective of the concrete quality or method of curing used, thicker coatings of zinc (up to 1420 gm/m^2 [4.65 oz/ft^2]) resulted in a shorter time to corrosion-caused concrete cracking. This test result indicates that the greater amount of galvanizing the greater the amount of corrosion products available to cause concrete cracking. This could indicate that the galvanizing corrodes rapidly in salt contaminated concrete. Otherwise there should be no difference in time to cracking for different thicknesses of zinc.

Electrical potential measurements indicate that galvanized steel can assume electrically "noble" potentials in low salt concrete and initially serve as a cathode to cause accelerated corrosion of both galvanized and black steel in highly salt contaminated concrete. The amount of corrosion that occurs will depend upon many variables such as polarization, anode to cathode area, etc.

On the basis of data plots, it was estimated that the lower mean potential of galvanized steel in concrete exposed to tap water was about -0.36 volt SCE with a standard deviation of about 0.12 volt (see Figure 5). However, it was not determined whether or not this or other potentials indicates a passive or noncorroding condition for the galvanized steel. But, zinc and steel corrosion products were observed on the surfaces of the steel bars. As a result, in concrete of variable salt concentration, there does not seem to be definitive half cell potential that would clearly indicate an active (corroding) or passive (non-corroding) condition of the zinc.

It appears that zinc behaves similarly to steel in salt contaminated concrete, it corrodes and causes concrete cracking.

Zinc does not have a consistent half cell potential in concrete whereby it can be depended upon to be a "sacrificial metal" and protect steel from corrosion by galvanic action.

In salt contaminated concrete, the data indicated (see Figures 1-4) that galvanized steel can have a half cell potential which ranges between -0.62 and -1.02 volts SCE (potentials within the limits of standard deviation). It is assumed that such potentials indicate an active or corroding state for the galvanized steel.

Also, the potential measurements show that it is possible that galvanized steel could, under some conditions, initiate corrosion of itself in salt-free concrete. The potential of zinc in relatively low salt-containing concrete can vary between about -0.19 to -0.75 volts SCE (see Figure 5) which could result in a galvanic voltage difference of 0.56 volts to initiate localized corrosion of itself. The amount and rate of corrosion will depend upon many variables.

In tap water galvanized steel corroded initially in relatively salt-free concrete and, after about 600 days of test, caused three out of 5 moist cured specimens to crack (see Figure 5). The five steam cured specimens did not have concrete cracking.

Concrete Curing

In this series of tests, as well as in those previously reported (8,16), there is a more rapid penetration of chloride into steam cured concrete and earlier corrosion of the imbedded steel as compared to a water cured concrete of the same quality.

Concrete Absorption

Concrete absorption or porosity, per se, indicated that it had a significant effect on the results of the corrosion behavior of galvanized steel. The more absorptive the concrete, the greater the differential in time between cracking caused by corrosion of galvanizing as compared to black steel. However, concrete absorption is not a reliable indicator of the protective qualities of concrete when the value is controlled by variables other than cement factor (8).

It is likely that the corrosion products are partially absorbed by the adjacent mortar or aggregate in highly absorptive concrete thereby postponing internal pressure buildup by the corrosion products which can cause rupture of the concrete.

RESULTS

Galvanized and Black Steel

As shown on Figures 1 through 4, the time to initiation of corrosion (as measured by the change in half cell potentials) of galvanized and black steel in comparative concrete environments is similar irrespective of cement factor or method of curing.

The difference in the time to cracking of the concrete caused by either the corrosion of steel or zinc showed that in the relatively porous 279 kilograms of cement per cubic meter of concrete (5-sack, moist cured concrete), the mean time for 20 galvanized specimens to crack was 315 days, and for the concrete containing 20 black steel bars the mean time to cracking was 175 days. For the 279 kg/m³ (5-sack) steam cured specimens, the mean time to concrete cracking for the galvanized was 243 days while the black steel took 124 days.

In the dense 415 kg/m³ (7-1/2 sack) moist cured concrete, the mean time for the 20 galvanized steel specimens to crack the concrete was ⁵⁴⁹545 days, while only 7 out of 20 black steel specimens had cracked at the end of the test time of 622 days.

In the case of the galvanized steel specimens partially immersed in Sacramento city tap water (about 20 to 40 ppm cl), three moist cured concrete specimens out of the 5 cracked about 7.6 cm (3-inches) above the water line after about 600 days of test.

At the conclusion of the test period of 1700 days, all ten tap water specimens were opened for inspection of the galvanizing. On all but one specimen, relatively minor rust spots were observed on the zinc surface. The one exception was where rust was absorbed by the steam cured concrete and was on the surface of the metal for a distance of about 0.32 cm (1/8-inch).

A considerable quantity of zinc corrosion products were observed at the tap water line and below, while above the water line the zinc was generally free of corrosion products.

Three concrete samples from the 418 kg/m^3 (7-1/2 sack) concrete were chemically analyzed and found to contain about 100 parts per million (ppm) chromate as CrO_3 . This is estimated to be a greater quantity than the 70 ppm found necessary in cement pastes to prevent hydrogen gas evolution from zinc(9). There was minor evidence of gas evolution observed at the concrete-zinc interface, and many of the galvanized steel bars were exposed without significant evidence of mortar porosity ^{nor} ~~or~~ was it sticking to their surfaces. The source of the chromate was found to be in the aggregate and the cement.

A chemical analysis of the concrete section immersed in tap water resulted in the finding of about 3.3 kg/m^3 of chloride-ion (5.6 pounds) per cubic yard in the concrete. The chloride content of the atmospherically exposed concrete was found to be about 0.95 kg/m^3 (1.6 pounds per cubic yard). The source of the chloride in concrete was not determined.

For the underwater concrete sections exposed to the saturated sodium chloride solution the average amount of absorbed chloride was 353 kg/m^3 (63.3 lbs/cy).

Table 2 shows concrete absorption test results. From the consistency of results, there does not appear to be any indication that any differences in concrete absorption affected any comparative test results.

To further evaluate the relationship between zinc and concrete cracking, the 20 galvanized specimens in each test were first ranked in ascending order of actual weight of zinc and then separated into two groups of 10 each. The two groups consisted of 10 which had the lightest weight of zinc in the particular test series and the other group of 10 out of the total of 20 which had heaviest weight of galvanizing. Then the average days to concrete cracking for each group of 10 out of 20 in each test series was calculated and tabulated as shown on Tables 3 and 3a. In each case the group of bars with the heaviest galvanizing cracked first.

DISCUSSION

The test data showed that for greater weights of zinc coating, the concrete was caused to crack earlier. Also, since heavier weights of zinc coating resulted in earlier concrete cracking, it is obvious that the corrosion products of zinc exert sufficient pressure to crack a 2.5 cm (1-inch) thick concrete cover.

The potential of the galvanized bar in initially salt-free concrete was found to vary between -0.19 volts and -0.75 volts SCE. This voltage difference of: $-0.75 - (-0.19) = 0.56$ volts might result in localized corrosion of the zinc coating.

In the highly salt contaminated concrete the potential of the galvanized bar varied between -0.62 and -1.02 volts SCE which could cause sections of zinc to have a galvanic voltage difference of 0.40 volts which might induce localized corrosion of itself.

When zinc is in concrete of variable salt contamination (potential at 1.02 volts SCE [Figure 2]) and a potential of -0.19 volts SCE [Figure 5] then the corrosion of zinc in the salt contaminated concrete could be initiated by a maximum of about 0.83 volts driving the associated current flow.

For steel in concrete specimens exposed to a saturated sodium chloride solution it was reported(16) that the mean potential of corroding black steel was -0.36 volts SCE to a maximum mean of -0.48 volts SCE. Therefore, when black steel in salt contaminated concrete begins to corrode (potential of -0.36 to -0.48 volts SCE) and is electrically interconnected to galvanized steel in relatively low salt concrete (minimum potential of -0.19 volts SCE) then the "reversed polarity" zinc might cause the black steel to have accelerated corrosion as a result of the developed .17 to .28 volt differential.

For the average indicated range of half cell potentials of zinc (this report) and black steel in salt-free concrete(8,16), it seems likely that the tendency would normally be for the black steel to cause accelerated corrosion of galvanizing in salt free concrete.

Under certain conditions, zinc can reverse in polarity and may cause accelerated corrosion of black steel. For example, at temperatures of about 60°C (140°F) or above in aerated hot waters, it was determined(12) that zinc would not act as a sacrificial coating but would become noble and induce pitting of steel.

It was also found that waters high in carbonates increase the tendency of the polarity reversal of zinc to iron couple(13).

It was reported that the formation of ZnO as a corrosion product of zinc was responsible for the polarity reversal instead of the porous $\text{Zn}(\text{OH})_2$ or the basic zinc salt which is normally anodic to iron(14).

The compound ZnO is reported to be a semi-conductor which in aerated waters acts as an oxygen (O_2) electrode whose potential is noble to zinc and iron(15). A noble potential may accelerate the corrosion of metals with a less noble potential.

It was also reported that when zinc was used as an anode in water or dilute NaCl, the current output decreased gradually because of the insulating corrosion products formed on the zinc surface. In one series of tests, the current between zinc and iron decreased to zero in 60 to 80 days, and a slight reversal of polarity was reported(15).

From the preceding reports by others, it is obvious that it cannot be assumed that zinc will always be a sacrificial metal and thus inhibit or reduce the corrosion of black steel.

In other studies it was found that when zinc was placed in concrete, the high alkalinity of the cement caused it to react and evolve hydrogen gas(9,17). When mixing cement with distilled water researchers found that the resultant pH was 12.8(9) which is well into the alkaline range that is highly corrosive as well as causing hydrogen evolution from the zinc(9,18). It has also been reported that if CrO_3 is added to the mixing water in excess of 100 ppm(17), the evolution of hydrogen gas would be inhibited.

In short time tests, it was related that the corrosion rate of zinc is lowest between the pH range of 7 to 12(15) and is quite rapid when the pH is 12.5(15) or near the values of 12.6 or 12.7(9) or above.

In these tap water tests, black steel as a control for the galvanized steel specimens was omitted because previous but unreported testing by the authors over a period of about three years resulted in no observed corrosion of the bars in the same cement factor concrete as used in this test. Also since this test was to evaluate galvanizing it was originally thought that there would be no corrosion of the zinc, and they would be a control for the specimens exposed to the salt. But, such was not the case; however, the test in tap water of the galvanized specimens did demonstrate the wide range of half cell potentials that could be expected of zinc, and, the measured values are subject to a great deal more interpretation and investigation than anticipated.

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Table 1

Concrete Mix Variables - English Units

	5-sack Mix	6-sack Mix	7-1/2 sack Mix
Maximum Size Aggregate	3/4"	3/4"	3/4"
Cement Factor (94-lb. sacks)	4.97	5.95	7.49
Slump, Inches	3	2-1/2	3
Net W/C (by weight)	0.63	0.51	0.41
Gross W/C (by weight)	0.72	0.59	0.47
Air (entrapped), percent	2.15	2.6	1.6

Table 1a

Concrete Mix Variables - Metric Units

Maximum Size Aggregate, cm	1.9	1.9	1.9
Cement Content, Kg/m ³	277	332	418
Slump, cm	7.6	6.4	7.6
Net W/C (by weight)	0.63	0.51	0.41
Gross W/C (by weight)	0.72	0.59	0.47
Air (entrapped), percent	2.15	2.6	1.6

Table 2

Concrete Absorption

Cement Factor	Cure	Absorption, % by Volume*	
		For Galvani- zed Bars	For Black Steel Bars
5-sack (279 kg/m ³)	Moist	15.30	15.23
	Steam	15.53	15.64
6-sack (335 kg/m ³)	Moist	14.83	---
	Steam	14.84	---
7-1/2-sack (418 kg/m ³)	Moist	13.84	13.83
	Steam	13.42	13.48

*28-day values

Table 3
Weight of Zinc and Concrete Cracking
English Units

Cement Factor	Cure	Days to concrete Cracking		Weight of Zinc, Oz./Sq. Ft.*	
		Avg.	Std. Dev.	Avg.	Std. Dev.
5-sack	Moist	327	56	2.94	0.15
	Moist	302	48	3.41	0.25
5-sack	Steam	248 275	82	2.86	0.14
	Steam	239	75	3.21	0.12
7-1/2 sack	Moist	600	56	2.96	0.14
	Moist	498	123	3.69	0.57
	Steam	390	69	3.00	0.18
	Steam	381	182	3.73	0.35

*For 10 bars

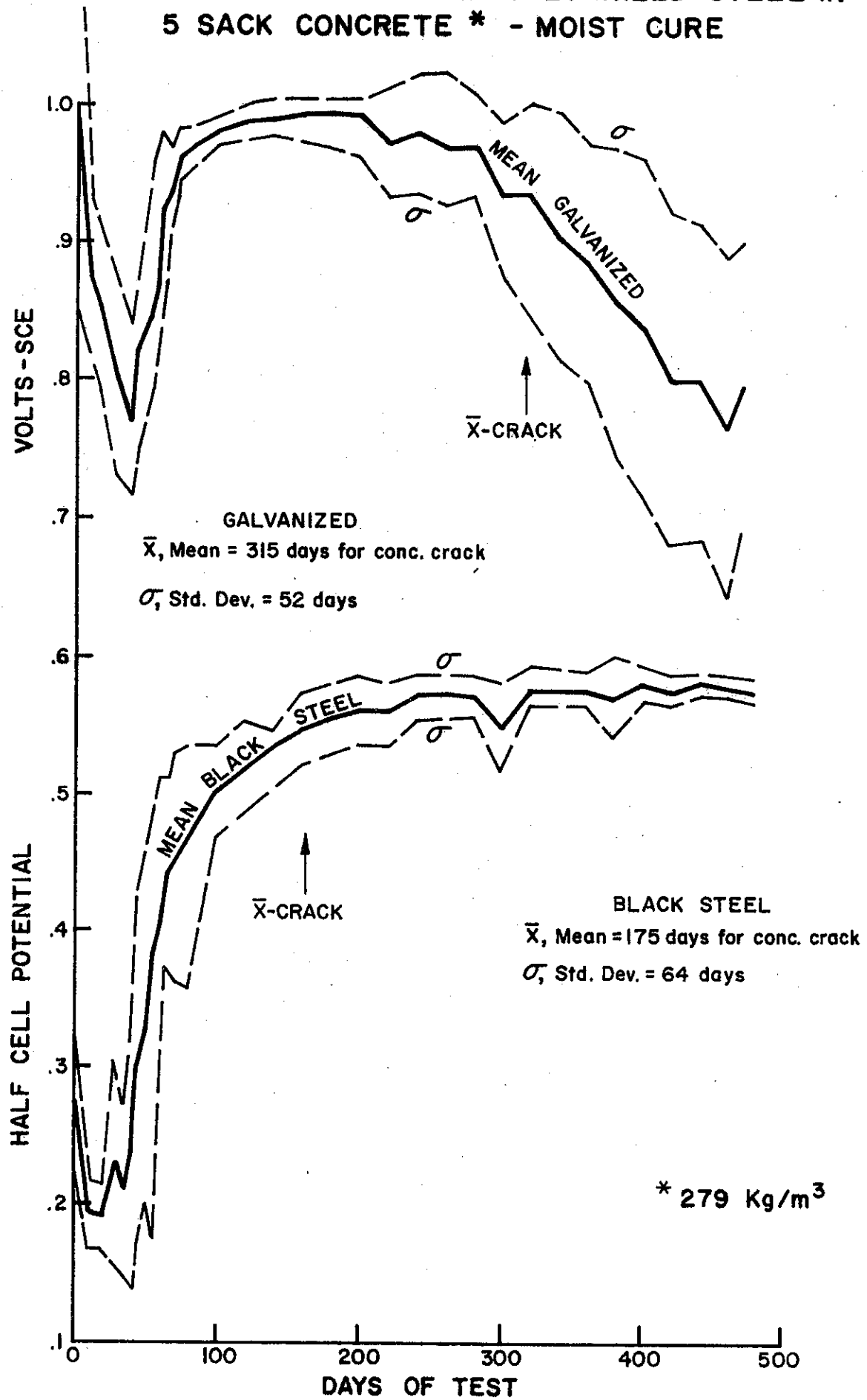
Table 3a
Weight of Zinc and Concrete Cracking
Metric Units

Cement Factor	Cure	Days to Concrete Cracking		Weight of Zinc,* Gm/m ²	
		Avg.	Std. Dev.	Average	Std. Dev.
279 Kg/m ³	Moist	327	56	895.4 897.2	46.7 45.8
	Moist	302	48	1040.6 1038.1	76.3 71.6
	Steam	248 275	82	873.7 872.8	41.5 42.7
	Steam	239	75	979.6 979.9	36.6
	Moist	600	56	901.6 903.3	43.5 42.7
	Moist	498	123	1126.0 1124.2	173.9 173.0
418 Kg/m ³	Steam	390	69	916.0 915.5	55.4 54.9
	Steam	381	182	1138.3 1137.1	106.8 106.9

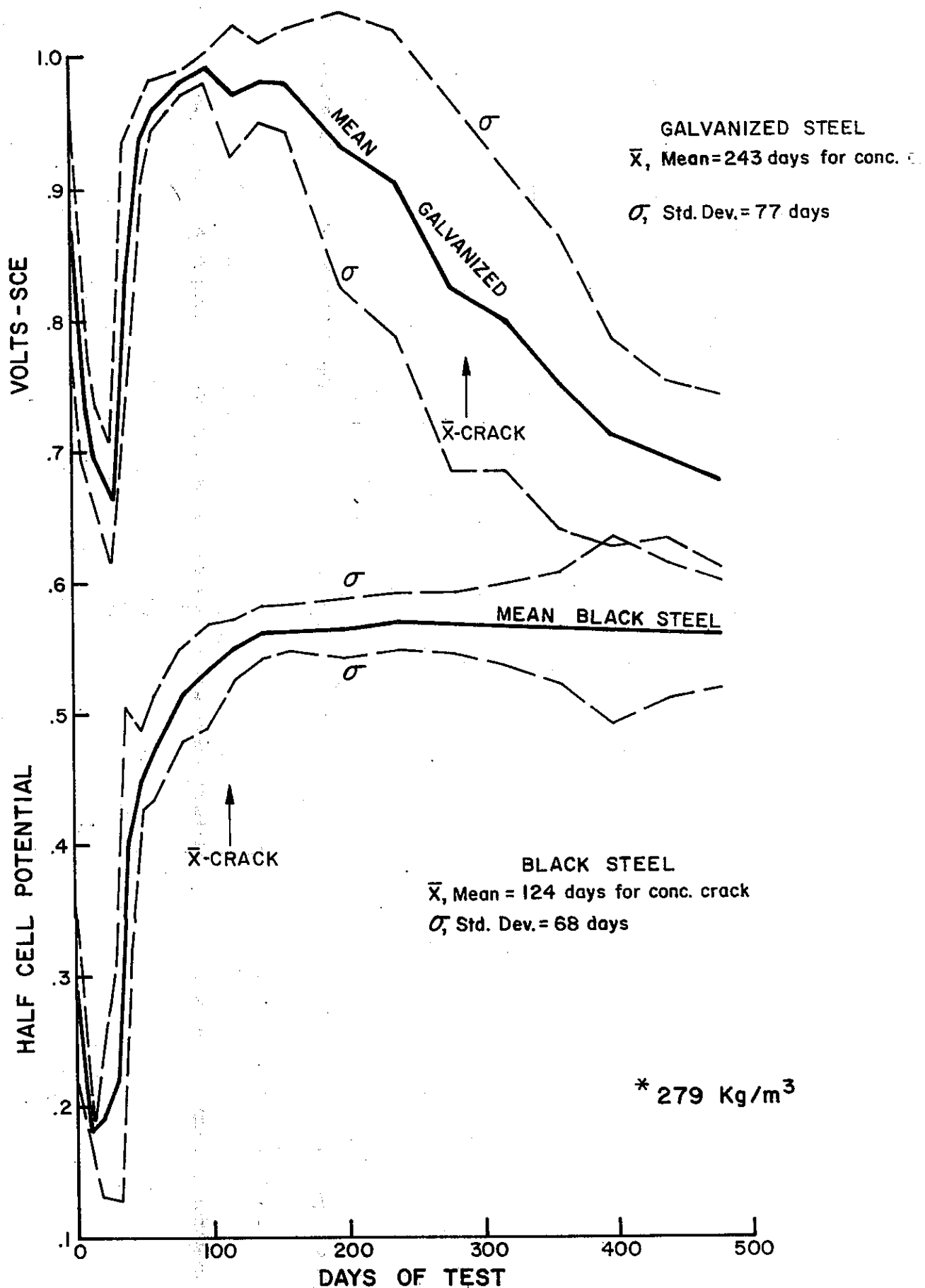
*For 10 bars

FIGURE 1

POTENTIALS OF BLACK AND GALVANIZED STEEL IN 5 SACK CONCRETE * - MOIST CURE



POTENTIALS OF BLACK AND GALVANIZED STEEL IN 5 SACK CONCRETE * - STEAM CURE



1.2 SACK CONCRETE - MOIST CURE

VOLTS - SCE

MEAN GALVANIZED

\bar{X} , Mean = 549 days for conc. crack.
 σ , Std. Dev. = 94 days.
 107

\bar{X} -CRACK

MEAN BLACK STEEL

* 418 Kg/m³

BLACK STEEL
 7 out of 20 conc. specimens cracked
 in test period of 622 days.

DAYS OF TEST

FIGURE 4
POTENTIAL OF BLACK AND GALVANIZED STEEL IN
7½ SACK CONCRETE* STEAM CURE

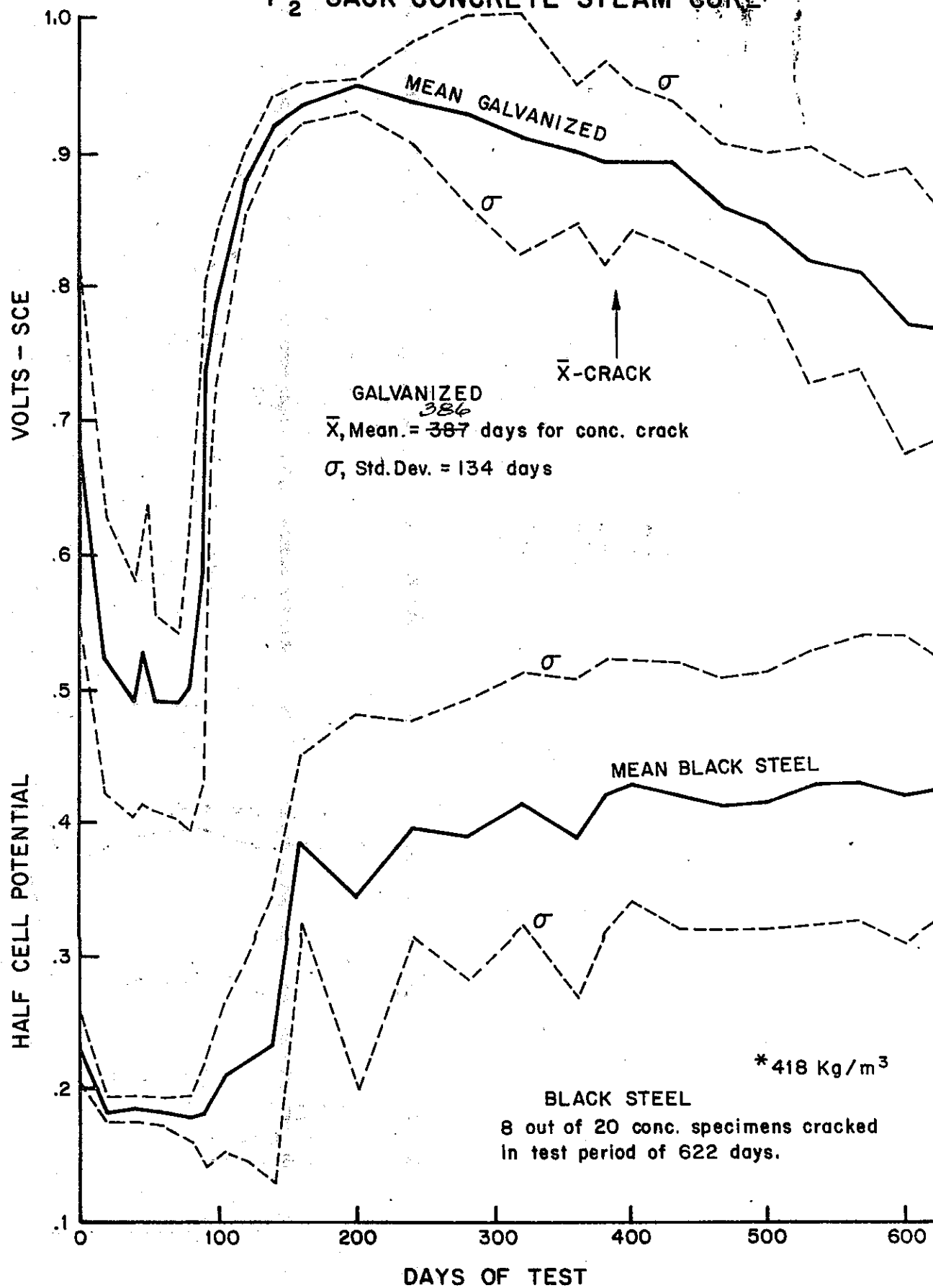
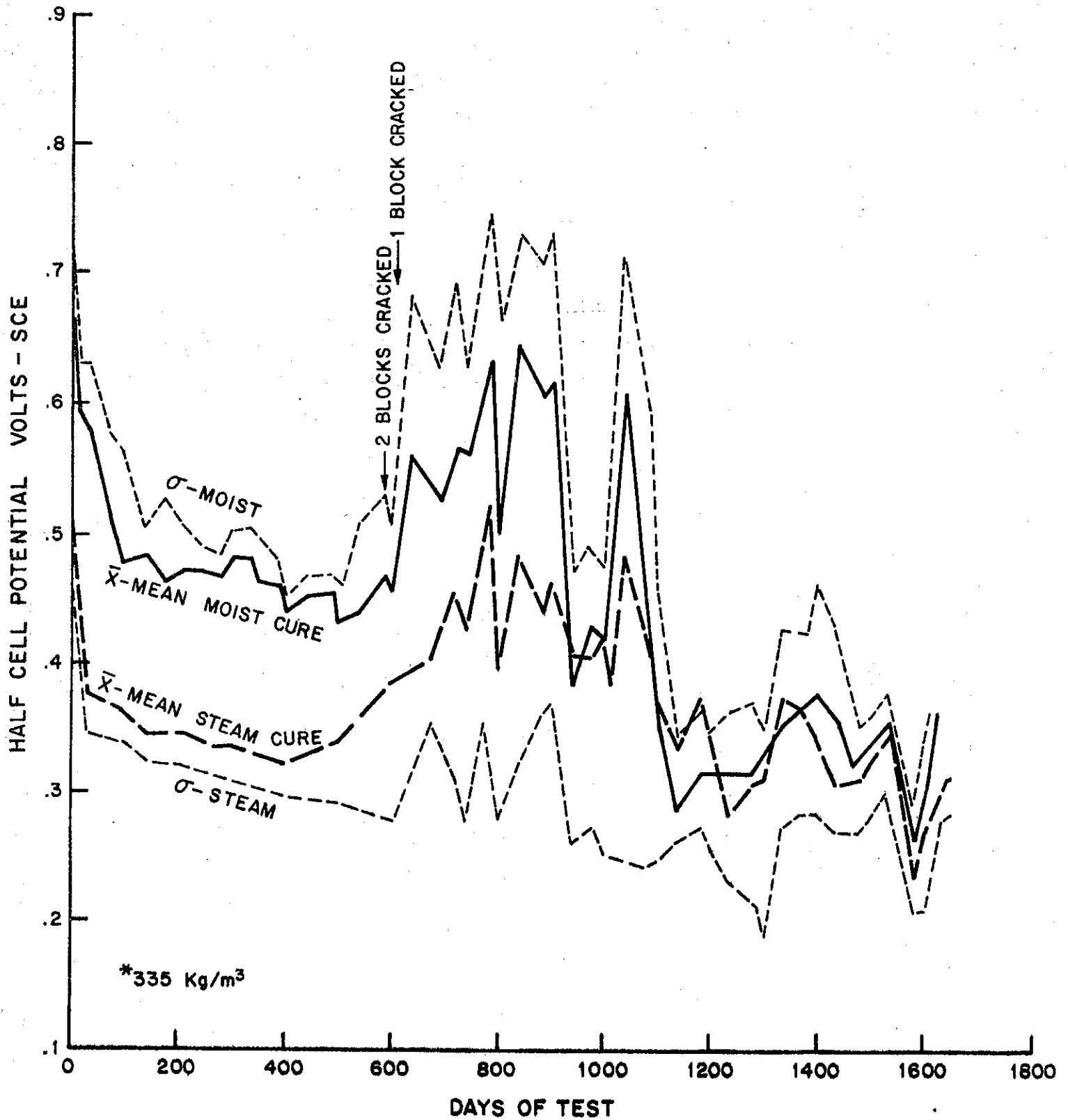


FIGURE 5

POTENTIAL OF GALVANIZED REINFORCING STEEL IN
6 SACK CONCRETE*-IN TAP WATER



11 327 1107 1114 1114

1114 1114 1114 1114 1114

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